The Aerosol-Generating Effect Among Noninvasive Positive Pressure Ventilation, High-Flow Nasal Cannula, Nonrebreather Mask, Nasal Cannula, and Ventilator-Assisted Preoxygenation

Tzu-Yao Hung, MD, PhD; Wei-Lun Chen, MD; Yung-Cheng Su, MD, MPH; Chih-Chieh Wu, MD; Chung-Chun Wang, MD, MS; Hsin-Ling Chen, MD, MS*; Shih-Cheng Hu, MD, PhD; Tee Lin, MD, PhD

*Corresponding Author. E-mail: taipeicityerprogram@gmail.com or bryansolitude@gmail.com.

Study objective: To evaluate aerosol dispersion and exposure risk during oxygenation therapy among health care personnel.

Methods: This study compared the aerosol dispersion effect produced through continuous positive airway pressure (CPAP), bilevel positive airway pressure (BiPAP), BiPAP with face coverings, a high-flow nasal cannula (HFNC) with face coverings, nasal cannula oxygenation (NCO) at 15 L/min with face coverings, nonrebreather mask (NRM), and ventilator-assisted preoxygenation (VAPOX) during oxygenation therapy at a minute ventilation of 10 L/min and 20 L/min. The length and width of aerosol dispersion were recorded, and aerosol concentrations were then detected at a mannequin's head, trunk, and feet.

Results: The average length dispersion distance of CPAP was 47.12 cm (SD, 12.56 cm), of BiPAP was 100.13 cm (SD, 6.03 cm), of BiPAP with face coverings was 62.20 cm (SD, 8.46 cm), of HFNC with face coverings was 67.09 cm (SD, 12.74 cm); of NCO with face coverings was 85.55 cm (SD, 7.28 cm); and of NRM was 63.08 cm (SD, 15.33 cm); VAPOX showed no visible dispersion. The aerosol concentrations at the feet under CPAP and at the head under BiPAP were significantly higher than those observed without an oxygen device. Compared with no oxygen device, the aerosol concentration with HFNC was higher at the mannequin's head, trunk, and feet; whereas it was lower with VAPOX and NRM. Moreover, when translated to the number of virus particles required to infect medical personnel (Nf), VAPOX took more time to achieve Nf than other devices.

Conclusion: Strong flow from the oxygenation devices resulted in increased aerosol concentrations. CPAP at the feet side, BiPAP at the head side, HFNC, and NCO with face coverings significantly increase aerosol exposure and should be used with caution. Aerosol concentrations at all positions were lower with NRM and VAPOX. [Ann Emerg Med. 2022;80:22-34.]

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INTRODUCTION

Background

Coronaviruses are the pathogens responsible for several outbreaks of serious emerging infectious diseases, including the coronavirus disease 2019 (COVID-19) pandemic.[1] Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) can be detected in the saliva and upper airway discharge of infected individuals and transmitted to a person nearby via droplets or aerosol microdroplets through coughing, sneezing, talking, and breathing.[2] Aerosol-generating procedures, such as tracheal intubation, noninvasive ventilation, manual venstilation, mechanical ventilation, cardiopulmonary resuscitation, tracheostomy, and nasogastric tube insertion, may increase the risk of infection.[3-6]

Multiple studies have reported that 19.0% to 75.2% of patients with COVID-19 develop hypoxia with progression to respiratory failure in severe cases.[7-11] Oxygenation therapy is universally recommended in studies and guidelines for managing patients with COVID-19 and improving intubation safety.[6,12-21] These techniques can be divided into 2 categories. The first category includes oxygenation techniques without positive pressure, such as nonrebreather mask (NRM), high-flow nasal cannula (HFNC), and nasal cannula oxygenation (NCO).[13,14,16,17,22-24] The second category includes oxygenation techniques with positive pressure, involving a closed system and the use of a sealed nasal or oronasal mask, such as noninvasive ventilation (eg, continuous positive airway pressure [CPAP]), bilevel positive airway pressure (BiPAP), and ventilator-assisted

Editor's Capsule Summary

What is already known on this topic
Airway management can generate infectious aerosols that contaminate the surrounding environment.

What question this study addressed
The aerosol dispersion levels and patterns associated with respiratory treatment options frequently used in the emergency department.

What this study adds to our knowledge
Nonrebreather mask and ventilator-assisted preoxygenation demonstrated the lowest levels of dispersion. Other forms of respiratory support, including nasal cannula, continuous positive pressure ventilation, and bilevel positive airway pressure, generated substantially greater aerosol dispersion.

How this is relevant to clinical practice
Insight into aerosol dispersion risks can enable clinicians to select respiratory support measures that provide adequate oxygenation while limiting the dispersion of infective aerosols.

Research we would like to see
How factors such as coughing, patient respiratory patterns and movement, and overall room airflow affect the concentration and dispersion of infective aerosols.

preoxygenation (VAPOX).[14,15,19,21,22] As opposed to CPAP and BiPAP, which have only one exhalation port, VAPOX has a double-limb circuit (inhalation and exhalation) and thus can avoid aerosol dispersion if applied with proper face mask ventilation technique. In addition to preoxygenation before intubation, VAPOX can be potentially used for oxygenation purposes. Positive pressure can reduce the anatomical dead space, alleviate pathologic shunts, and enhance the efficiency of oxygenation to avoid intubation or help preoxygenation before intubation.[11,12,15,19]

Droplets and aerosols could spread throughout an environment via the expiration, coughing, and sneezing of patients with COVID-19 and are potentially hazardous, especially for people in close contact or an enclosed space.[22,25-28] Meta-analyses have suggested that HFNC oxygenation and noninvasive ventilation are effective in obviating the need for intubation in patients with COVID-19 and respiratory failure.[20,24,29,30] However, the dispersion of aerosols and droplets is a concern during the use of HFNCs, which are maintained at relatively high flow rates (30 to 70 L/min) to prevent desaturation.[31] The safety of oxygenation with HFNC and noninvasive ventilation remains a subject of intense debate.[24,31-33]

With regards to comparing the dispersion distances with various oxygenation devices, studies have used a tracer gas with aerosol-sized particles (diameter of 0.5 to 0.7μm) with a mannequin, visualizing the flow field by using laser projection.[33-35] Aerosol droplets, with a diameter less than 5 μm, can suspend in an unventilated space for at least 5 to 9 minutes.[25,36] Smith et al[36] simulated the SARS-CoV-2 aerosol transmission with an atomized glycerol mixture to evaluate the persistence of aerosol and the possibility of infection during coughs. To evaluate the aerosol dispersion range during oxygen therapy, our primary objective was to determine the length and width of the dispersion distance of aerosol from the mouth of the mannequin. The secondary objective was to evaluate the risk of aerosol exposure by determining the aerosol concentration at the mannequin's head, trunk, and feet.

Importance

Oxygenation may obviate the necessity of intubation in patients with COVID-19. However, aerosol dispersion associated with a strong flow or positive pressure may increase the exposure risk among health care personnel.

Goals of This Investigation

The present study investigated the aerosol dispersion effect of CPAP, BiPAP, NRM, VAPOX, and face coverings with BiPAP, HFNC, and NCO to increase vigilance among health care personnel when oxygenating patients with potentially infectious respiratory diseases. Furthermore, the differences in the dispersion effects among patients with various lung pathologies were also examined.

MATERIALS AND METHODS
Study Design and Setting

This simulation study involved no human participants; thus, it was exempted from the Taipei City Hospital Research Ethics Committee. This in situ study was conducted in the resuscitation room of the emergency department (ED) of the Zhong-Xing Branch of Taipei City Hospital, a metropolitan teaching hospital and a COVID-19 designated institution. More than 30,000 patients are admitted to the ED each year. The background flow of the resuscitation room from the top of the space to the 4 vents

at the bottom of each corner occurs in a downward direction, with 12 air changes per hour. The average room temperature was 21.6±0.3 °C. The relative humidity was 57.7%±1.2%. A high-fidelity simulation mannequin (Airway Management Trainer; Laerdal) was placed faceup at an incline of 30 degrees. Respiration was fixed at 25 respirations per minute, with a minute ventilation rate of 10 and 20 L/min, and maintained through a connection to a 3-dimensional–printed version of the Massachusetts Institute of Technology Emergency Ventilator and a smoke particle generator (MPL-I003, Tong-Da industry company). With the use of atomized glycerol (1% glycerol and 99% water mixture) as a tracer gas and a high-sensitivity camera (ORCA-Flash 4.0 V2 digital CMOS camera, Hamamatsu Co.) for recording, large-scale particle image velocimetry was performed in the sagittal and coronal planes under green laser irradiation (Figure 1A). A light-scattering photometer was used at a sampling rate of 28.3 L/min over 3 minutes to detect the aerosol concentrations at the head, trunk, and feet of the mannequin. The tracer gas was poly-alpha-olefin (PAO) (diameter, 0.5 to 0.7μm) (Figure 1B).

During BiPAP oxygenation, which was applied using a Sullivan VPAP II ST-A (ResMed Co.), the exhalation positive airway pressure (EPAP) and the inhalation positive airway pressure (IPAP) were 5 and 15 cmH$_2$O, and the respiratory rate was fixed at 15 respirations per minute. During CPAP oxygenation, which was applied using an AirFit N20 Nasal CPAP Mask Kit (ResMed Co.), the pressure was set at 5 to 15cmH$_2$O, and the respiratory rate was fixed at 15 respirations per minute. During HFNC oxygenation, which was applied using the Humidoflo HF-2970 system (Great Group Medical Co., Ltd.), the flow rate was set at 30 and 70 L/min. During NCO and NRM oxygenation, the flow rate was 15 L/min. As for VAPOX, the pressure support and positive end-expiratory pressure were 10 and 5 cmH$_2$O, respectively; the respiratory rate was 15 respirations per minute. To generalize the study result, the mannequin's face was covered with a surgical mask under the BiPAP, HFNC, and NCO subgroups.

Interventions

The reference setting did not include the use of any oxygenation devices. Eight preoxygenation settings were evaluated: CPAP oxygenation at 5 to 15cmH$_2$O, BiPAP oxygenation (IPAP of 15 cmH$_2$O and EPAP of 5 cmH$_2$O), BiPAP with a face covering, HFNC oxygenation with face coverings at flow rates of 30 and 70 L/min, NCO with a face covering at 15 L/min, NRM oxygenation at 15 L/min, and VAPOX with pressure support and positive end-expiratory pressure of 5 and 10 cmH$_2$O.

Measurements

Particle image velocimetry, performed to investigate the aerosol movement, involved the use of a high-sensitivity camera operating in 2 planes (sagittal and coronal). The data were analyzed and presented as distances and vector graphs. First, the background flow field was recorded. Next, 8 oxygenation devices were used to measure the dispersion distance in the sagittal and coronal planes. Aerosol concentrations at the head, trunk, and feet of the mannequin were continuously detected over 3 minutes under the same settings. Between measurements, the detection began only after the PAO concentration fell below the baseline of 50 ppm.
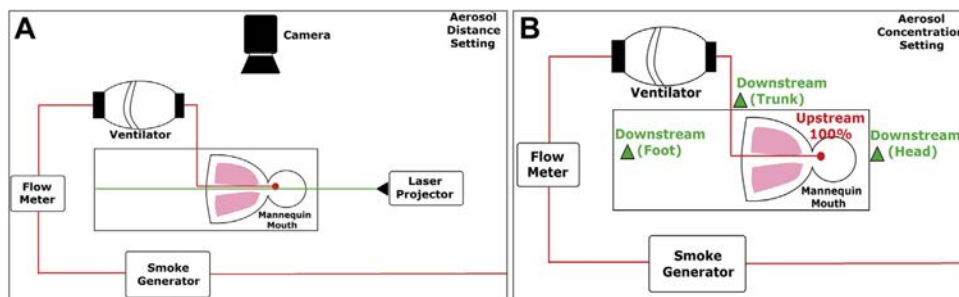

Figure 1. A, Aerosol distance setting diagram. A smoke generator and a flow meter were connected with a 3-dimensional–printed version of the Massachusetts Institute of Technology Emergency Ventilator to create a fixed respiration rate of 25 respirations per minute, with minute ventilation rate of 10 and 20 L/min. A green laser projector projected a plane to outline the aerosol dispersion. The dispersion of atomized glycerol was recorded by a high-sensitivity camera and was latterly analyzed with a large-scale particle image velocimetry program. *B*, Aerosol concentration setting diagram. The PAO was used as a tracer gas. The aerosol concentration at the mouth of the mannequin was defined as upstream and 100%. The aerosol concentrations were measured with a light-scattering photometer at 3 spots (downstream at the head, trunk, and feet of the mannequin) to detect the aerosol exposure of health care workers.

Outcomes

The primary outcome was the dispersion distance (sagittal × coronal) of aerosols with and without the use of oxygenation devices at minute ventilation rates of 10 L/min and 20 L/min. The secondary outcome, which was evaluated to determine the hazardous effects of aerosol exposure, was the aerosol concentration at the head, trunk, and feet of the mannequin in the 6 different settings compared with those under the conditions of no oxygenation device at minute ventilation of 10 and 20 L/min. The visualized flow fields of 6 devices were also analyzed to correlate the results of the interpretation of aerosol dispersion distances and concentrations.

Analysis

Student's *t* tests were conducted to evaluate the mean percentage differences among each of the oxygen device settings. Analyses were performed using the SAS System for Unix, version 9.4 (SAS Institute, Inc.), and STATA software, version 15.1 (StataCorp). In total, 36 comparisons—9×2×2 possibilities—were made (involving 1 reference group and 8 oxygenation devices, the length and width of aerosol dispersion, and minute ventilation rates at 10 and 20 L/min). Regarding the measurement of aerosol concentrations at the head, trunk, and feet, 54 comparisons (9×3×2 possibilities) were made (involving 1 reference group and 8 oxygenation devices; aerosol concentrations at the head, trunk, and feet; and minute ventilation rates of 10 and 20 L/min). We have accounted for multiple testing issues and addressed the multiple comparisons problem by using Bonferroni correction, adjusting the confidence interval to 99.9% because of the large number of pairwise comparisons. We measured the length and width of aerosol dispersion 100 times in an interval of 3 minutes for the reference and the 8 study groups. We measured the aerosol concentrations at the head, trunk, and feet around the mannequin 450 times in an interval of 3 minutes for the reference and study groups.

RESULTS

The resuscitation room with a high-efficiency particulate air box on the top brought a downward flow. Particle image velocimetry revealed that under CPAP oxygenation and minute ventilation at 20 L/min, the concentrated aerosols were ejected up to 36 cm and pushed down to the left by the room ventilation flow. Under BiPAP oxygenation, the concentrated aerosols were compressed by the downward flow in the room and assembled at the head of the mannequin. Under HFNC oxygenation with face coverings at a flow rate of 70 L/

min, the concentrated aerosols dispersed higher, wider, and more rapidly than under NCO with face coverings. Under NRM oxygenation, the aerosols dispersed directly to the top of the head in the sagittal plane (Figure 2). Overall, compared to the reference distance, the length of the dispersion distance in the sagittal and coronal planes was greater with the use of oxygenation devices (for all, except the CPAP oxygenation at the minute ventilation of 20 L/min, NRM oxygenation at the minute ventilation of 10 L/min, and VAPOX) (Table 1). At a minute ventilation of 10 L/min, the areas of aerosol dispersion under all devices tended to be elongated except CPAP oxygenation. At a stronger ventilation of 20 L/min, the areas became more square-shaped, except BiPAP, NCO with face covering, and NRM. The longest dispersion distance was with BiPAP and NCO with face coverings at a minute ventilation of 10 L/min, BiPAP without a face covering, and NCO with a face covering at a minute ventilation of 20 L/min. As for VAPOX, no visible dispersion was noted (Table 1).

The aerosol concentrations were higher at the feet of the mannequin than at the head or trunk (feet >head>trunk), irrespective of whether an oxygenation device was used (except in the case of BiPAP; BiPAP with a face covering; and NRM oxygenation, where the concentration was the highest at the head) (Table 2). At a mannequin minute ventilation of 10 L/min, the aerosol concentrations at the head were significantly lower with the use of oxygenation devices than the reference group (except in the case of BiPAP, BiPAP with a face covering, and HFNC oxygenation with a face covering at a flow rate of 30 L/min). At the same minute ventilation, only the aerosol concentration at the trunk under HFNC oxygenation and NCO with face coverings was significantly higher than the reference group (Table 2). At the feet, aerosol concentrations under CPAP, HFNC oxygenation, and NCO with face coverings were higher than those in the reference group (Table 2). Under NRM oxygenation and VAPOX, aerosol concentrations at the head, trunk, and feet were all lower than those in the reference group (Table 2). Under a higher mannequin minute ventilation rate of 20 L/min, the concentrations of aerosols at the head from all oxygenation devices (except the CPAP, BiPAP, and HFNC oxygenation with a face covering at 70 L/min) were lower than the reference group. At the trunk, the corresponding concentrations from CPAP oxygenation and HFNC oxygenation with face coverings were the only group higher than the reference. At the feet, the aerosol concentrations under CPAP oxygenation and HFNC at a flow rate of 70L/min were higher than the reference group (Table 2). Regardless of position, aerosol concentrations
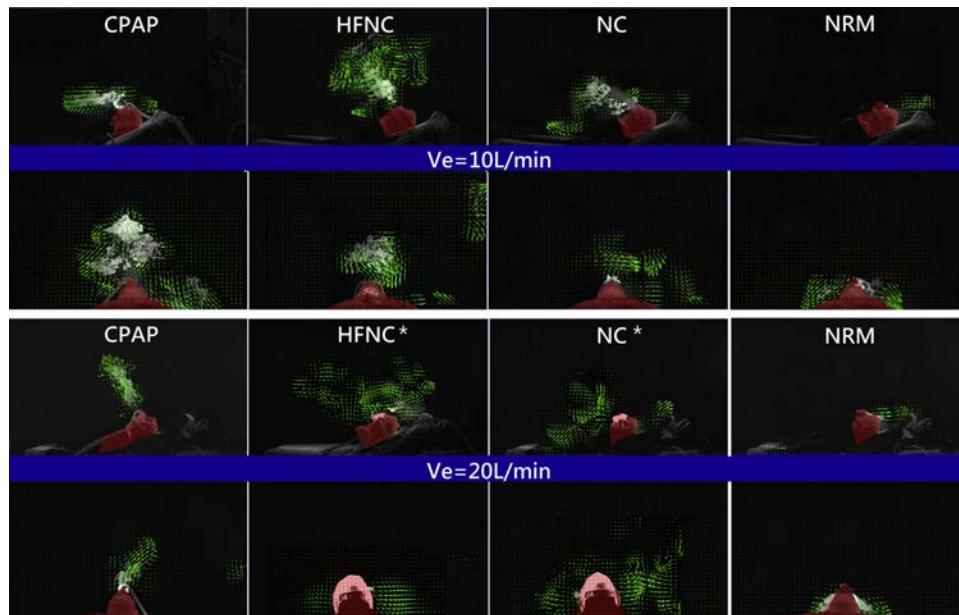
Figure 2. Aerosol movement with a velocity vector (green arrows) under particle image velocimetry. Columns 1, 2, 3, and 4 present the results for a NRM oxygenation, nasal cannula (NC) oxygenation, HFNC oxygenation at a flow rate of 70 L/min, and CPAP oxygenation, respectively. Rows 1 and 2 present the results in the sagittal and coronal planes at a minute ventilation (Ve) of 10 L/min, and rows 3 and 4 present the corresponding results at a Ve of 20 L/min. Under NRM oxygenation (column 1), aerosols dispersed to the top of the head of the mannequin and to both sides of the mask, but no visible flow to the feet was noted. The upper rows of columns 2 and 3 indicated HFNC and NC oxygenation (Ve=10 L/min). Lower rows of columns 2 and 3 were HFNC and NC with face coverings at Ve=20 L/min (HFNC* and NC*). Under CPAP oxygenation (column 4), higher dispersion (relative to that under HFNC oxygenation at Ve=10 L/min) was observed in the coronal plane but not in the sagittal plane. Under CPAP oxygenation at a flow rate of 20 L/min (column 4, rows 3 and 4), concentrated aerosols were released from the exhalation port on the mask. No visible aerosol movement was detected under VAPOX (not shown).

under NRM oxygenation and VAPOX remained lower than the reference concentration.

LIMITATIONS

This was a simulation study and, therefore, may not be indicative of clinical reality. We simulated ventilation on a mannequin by using a 3-dimensional–printed ventilator at minute ventilation rates of 10 and 20 L/min; this may not be compatible with the physiology of the human lung, given that a patient with respiratory failure may have a higher minute ventilation of up to 40 L/min. Nevertheless, trends could be identified in the results. Moreover, we could simulate exhalation but not inhalation. However, our main goal was to observe changes in airflow and aerosol concentrations during exhalation. Thus, the impact of human inhalation was of little concern in the present investigation.

Regarding particle image velocimetry, we could only analyze the airflow pattern in a 2-dimensional field. Because this type of analysis is not quantitative, we

determined the dispersion distances and aerosol concentrations to quantify the primary and secondary outcomes and to compare the groups.

The aerosols were detected over 3 minutes. The result may not be applied with a longer period of oxygenation. In particular, health care personnel should be aware that oxygenation devices can increase aerosol exposure, particularly at patients' feet. They should adopt a stepwise strategy for oxygenation to manage restrictions in terms of space and resources.

The SARS-CoV-2 aerosol gas clouds may produce differently with different measures humidity in the room, the temperature, and the pre-existed airflow in space. Virus viability may change easily depending on the local environment. The study was conducted in a ventilated room with 12 air changes per hour and downward airflow from the top of the room. When in a nonventilated room, the aerosols could suspend much longer. The downward airflow in the study room suppressed the ejected aerosol dispersion and may underestimate the aerosol dispersion in another setting. In particular, the study result did not

Table 1. The aerosol dispersion distance in length and width between the reference baseline and 6 oxygenation methods under mannequin ventilation rate at 10L/min and 20 L/min were evaluated by t tests. P value was defined significant if less than .001 by Bonferroni correction.

Minute Ventilation=10 L/min					Minute Ventilation=20 L/min				
Dispersion Length						**Dispersion Length**			
	Mean (cm)	Standard Deviation	Mean Difference	99.9% CI of Mean Difference		Mean(cm)	Standard Deviation	Mean Difference	99.9% CI of Mean Difference
Reference*	**33.96**	**10.22**			**Reference***	**51.49**	**19.47**		
CPAP	51.10	37.52	−17.14	−30.28-−4.00	CPAP	47.12	12.56	4.37	−3.38-12.13
BiPAP	48.14	6.33	−14.18	−18.21-−10.15	BiPAP	100.13	6.03	−48.64	−55.52-−41.76
BiPAP[†]	72.70	5.99	−38.74	−42.71-−34.77	BiPAP[†]	62.20	8.46	−10.71	−17.85-−3.57
HFNC30[†]	43.46	13.99	−9.50	−15.30-−3.71	HFNC30[†]	64.31	14.39	−12.82	−20.92-−4.72
HFNC70[†]	60.24	7.85	−26.28	−30.59-−21.97	HFNC70[†]	67.09	12.74	−15.60	−23.39-−7.81
NC[†,‡]	63.62	7.01	−29.66	−33.80-−25.51	NC[†,‡]	85.55	7.28	−34.06	−41.06-−27.06
NRM[§]	61.46	15.58	−27.51	−33.74-−21.27	NRM[§]	63.08	15.33	−11.59	−19.87-−3.31
VAPOX	No visible dispersion		33.96	30.49-37.43	VAPOX	No visible dispersion		51.49	44.89-58.09

Dispersion Width						**Dispersion Width**			
	Mean(cm)	Standard Deviation	Mean Difference	99.9% of Mean Difference Confidence Interval		Mean(cm)	Standard Deviation	Mean Difference	99.9% of Mean Difference Confidence Interval
Reference*	**14.02**	**4.68**			**Reference***	**10.07**	**4.54**		
CPAP	52.59	10.80	−38.57	−42.53-−34.61	CPAP	30.41	24.52	−20.35	−28.79-−11.91
BiPAP	45.75	2.30	−31.73	−33.48-−29.98	BiPAP	55.86	2.98	−45.80	−47.61-−43.98
BiPAP[†]	27.02	2.50	−13.00	−14.78-−11.22	BiPAP[†]	60.13	2.99	−50.07	−51.89-−48.25
HFNC30[†]	20.48	4.46	−6.46	−8.62-−4.30	HFNC30[†]	51.46	3.09	−41.39	−43.23-−39.55
HFNC70[†]	25.85	2.18	−11.83	−13.56-−10.09	HFNC70[†]	50.41	3.49	−40.34	−42.26-−38.43
NC[†,‡]	23.70	4.16	−9.68	−11.78-−7.59	NC[†,‡]	49.86	3.62	−39.79	−41.74-−37.85
NRM[§]	17.22	14.96	−3.20	−8.49-2.09	NRM[§]	35.45	12.09	−25.38	−29.73-−21.03
VAPOX	No visible dispersion		14.02	12.43-15.61	VAPOX	No visible dispersion		10.07	8.53-11.61

CI, confidence interval; NC, nasal cannula.
*No oxygenation devices.
[†]Mannequin's face was covered with surgical mask.
[‡]NC at 15 L/min.
[§]NRM at 15 L/min.

directly correlate between droplet spread in living humans versus the glycerol model.

DISCUSSION

Viral aerosols can spread continuously during oxygenation, endangering health care personnel and possibly leading to nosocomial infections. This is particularly relevant in the COVID-19 pandemic era; such infections are likely to occur at overcapacity hospitals. High-flow oxygenation devices can mitigate hypoxia in patients with COVID-19 and obviate the need for intubation. However, it can also substantially increase the dispersion of aerosols within an enclosed space. Few studies have discussed the hazardous effects of oxygenation; consequently, this may lower the vigilance of the health care personnel to wear adequate personal protective equipment.

Hui et al[37] (2014) reported that the maximum dispersion distance of NCO at flow rates of 1, 3, and 5 L/min were 30, 36, and 42 cm, respectively. At flow rates of 6, 8, 10, and 12 L/min under NRM oxygenation, the maximum dispersion distance ranged from 0.6 to 10.0 cm. The researchers also performed noninvasive ventilation using a BiPAP device, the expiratory positive airway pressure, which was maintained at 4 cmH$_2$O. The

Table 2. The mean differences and 99.9 % confidence interval of 8 oxygenation methods concentrations and the reference concentration in parts per million (ppm) at the head, trunk, and foot side of the mannequin.

	Minute Ventilation = 10 L/min						Minute Ventilation = 20 L/min			
	Mean (ppm)	Standard Deviation	Mean Difference	99.9% CI of Mean Difference			Mean (ppm)	Standard Deviation	Mean Difference	99.9% CI of Mean Difference
Reference*	598.20	284.38			**H**	**Reference***	907.03	159.90		
CPAP	327.57	178.26	270.63	219.05-322.21		CPAP	1012.56	1113.65	−105.52	−278.07-67.03
BiPAP	1088.66	1147.91	−490.46	−674.46-−306.46	**E**	BiPAP	1054.62	737.25	−147.59	−265.23-−29.95
BiPAP†	778.57	670.20	−180.37	−293.42-−67.33	**A**	BiPAP†	827.58	555.86	79.45	−10.66-169.57
HFNC30†	750.42	1328.40	−152.22	−364.11-59.67	**D**	HFNC30†	827.84	298.18	79.19	26.68-131.70
HFNC70†	567.41	995.28	30.79	−130.54-192.11		HFNC70†	1096.50	277.85	−189.47	−239.19-−139.75
NC†,‡	323.67	100.41	274.52	228.05-321.00		NC†,‡	553.48	286.19	353.55	302.69-404.41
NRM§	443.68	134.00	154.52	106.18-202.87		NRM§	595.96	206.88	311.07	271.08-351.06
VAPOX	105.39	38.47	492.81	448.60-537.01		VAPOX	284.35	114.31	622.68	592.61-652.75
Reference*	340.49	161.77			**T**	**Reference***	565.54	137.68		
CPAP	284.75	458.15	55.74	−19.03-130.51	**R**	CPAP	719.04	948.20	−153.50	−300.45-−6.55
BiPAP	318.89	109.68	21.60	-8.56-51.75	**U**	BiPAP	440.06	114.41	125.48	97.90-153.05
BiPAP†	194.93	83.53	145.56	117.49-173.63	**N**	BiPAP†	277.66	78.90	287.88	263.49-312.27
HFNC30†	612.59	226.12	−272.10	−315.19-−229.00	**K**	HFNC30†	718.29	296.65	−152.75	−203.57-−101.94
HFNC70†	707.43	211.69	−366.94	−408.21-−325.67		HFNC70†	808.21	223.91	−242.67	−283.42-−201.93
NC†,‡	597.51	161.16	−257.02	−292.32-−221.72		NC†,‡	337.70	125.36	227.84	199.14-256.55
NRM§	156.28	60.21	184.22	157.66-210.78		NRM§	241.48	87.78	324.06	299.08-349.05
VAPOX	129.11	60.12	211.38	184.83-237.94		VAPOX	193.63	57.07	371.91	349.08-394.73
Reference*	657.57	327.72			**F**	**Reference***	1359.36	368.38		
CPAP	1420.71	414.64	−763.15	−844.33-−681.96	**O**	CPAP	1773.34	1189.67	−413.98	−604.84-−223.12
BiPAP	391.64	110.67	265.92	212.62-319.23	**O**	BiPAP	517.25	120.96	842.11	782.59-901.62
BiPAP†	244.88	87.24	412.68	360.43-464.94	**T**	BiPAP†	384.94	84.07	974.42	916.44-1032.40
HFNC30†	738.91	426.68	−81.35	−164.69-2.00		HFNC30†	902.26	1252.73	457.11	253.69-660.52
HFNC70†	995.45	792.25	−337.88	−471.29-−204.48		HFNC70†	1092.30	612.61	267.06	156.24-377.88
NC†,‡	684.02	512.87	−26.46	−120.88-67.96		NC†,‡	627.17	340.72	732.19	654.83-809.56
NRM§	305.57	72.53	352.00	300.31-403.68		NRM§	478.08	64.96	881.28	823.92-938.64
VAPOX	272.52	90.70	385.05	332.70-437.40		VAPOX	358.75	60.90	1000.61	943.35-1057.87

*No oxygenation devices.
†Mannequin's face was covered with surgical mask.
‡NC at 15 L/min.
§NRM at 15 L/min.

distances of dispersion from the ResMed Mirage mask were 40 to 45 cm when the inspiratory positive airway pressure was increased from 10 to 18 cmH$_2$O, whereas those of the Respironics ComfortFull 2 mask were 65 to 85 cm. As for the Respironics Image 3 mask, which was connected to a whisper swivel exhalation port, the distances were ≥95 cm.[37] Overall, as indicated by the maximum exhaled air dispersion distance, NRM oxygenation dispersed less than NCO, and noninvasive ventilation dispersed the farthest among all oxygenation devices. In another study by Hui et al,[33] (2019), the aerosol dispersion distances under HFNC oxygenation at flow rates of 10, 30, and 60 L/min were compared with those under CPAP oxygenation delivered at pressures ranging from 5 to 20 cmH$_2$O. Regarding the exhaled aerosol dispersion along the sagittal plane under normal lung conditions, during the application of HFNC oxygenation, the distance increased from

6.5±1.5 to 17.2±3.3 cm as the flow rate increased from 10 to 60 L/min. When the CPAP pressure was increased from 5 to 20 cmH$_2$O using nasal pillows, the distance increased from 18.6±3.4 to 26.4±2.7 cm. The researchers concluded that the dispersion distance was greater under CPAP than under HFNC oxygenation.[33] Loh et al[38] compared the dispersion distance of 2 coughs from 5 healthy adults. Greater distances were observed when the participants were receiving HFNC oxygenation (291±109 cm) than when they were not (248±103 cm). These studies focused only on the maximum distance (sagittal plane), providing inadequate information on spatial aerosol movement and potentially leading to the misinterpretation of results. Thus, the present study examined both the sagittal and coronal planes. With the 30-degree upright position of the mannequin at a minute ventilation of 10 L/min, the aerosols were distributed in an elongated ellipse
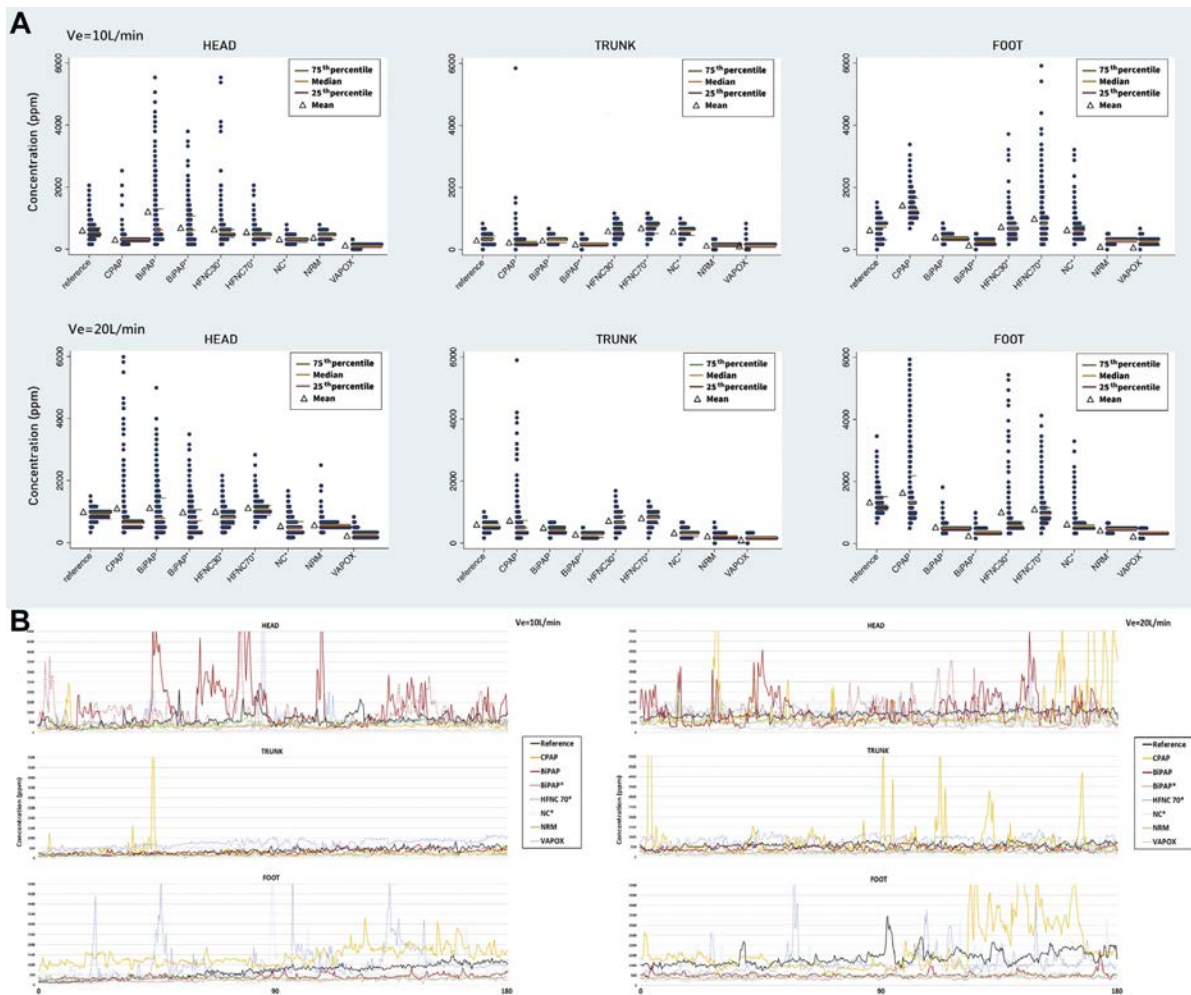
Figure 3. *A,* Dot plot of aerosol concentrations under the 8 oxygenation settings and at the reference baseline (ie, no oxygenation). Aerosol concentrations were higher when the mannequin ventilation rate was 20 L/min (compared with those at a rate of 10 L/min). Concentrations at the feet were higher under CPAP oxygenation, HFNC oxygenation with face coverings (HFNC 30* and HFNC 70*), NCO with face coverings (NCO*) than under NRM oxygenation, and VAPOX. At a mannequin ventilation rate of 10 L/min, outliers (ie, surges in aerosol concentrations) were noted under BiPAP oxygenation (BiPAP), BiPAP with face coverings (BiPAP*), HFNC 30*, and HFNC 70* at the head; CPAP oxygenation at the trunk; CPAP, HFNC 30*, HFNC 70*, and NCO* at the feet. At a mannequin ventilation rate of 20 L/min, outliers were observed for CPAP oxygenation, BiPAP, BiPAP*, HFNC 30*, HFNC 70*, and NRM therapy at the head; CPAP oxygenation at the trunk; and CPAP, HFNC 30*, HFNC 70*, and NCO* therapy at the feet. *B,* Aerosol concentrations under the 8 oxygenation settings and at the reference baseline (ie, no oxygenation) over 3 minutes. The black line is the reference baseline. The yellow, red, dotted red, dotted dark blue, dotted light blue, green, and gray lines denote the aerosol concentrations under CPAP, BiPAP, BiPAP with face coverings (BiPAP*), HFNC at a flow rate of 70 L/min with face coverings (HFNC 70*), NCO with face coverings (NCO*), NRM treatment, and VAPOX, respectively. The left and right columns present the minute ventilation at mannequin ventilation rates of 10 and 20 L/min. The top, middle, and bottom rows denote the concentrations at the head, trunk, and feet of the mannequin, respectively. Overall, the concentrations at the head and feet were higher than those at the trunk. Under CPAP therapy and HFNC oxygenation with face coverings, aerosol concentrations surged intermittently in all positions. As for BiPAP and BiPAP with face coverings, concentration surges were found only at the head. Under NCO with face coverings, the aerosol concentrations were consistently higher at the feet. Under NRM treatment, the concentration exhibited a small increase at the head with a ventilation rate of 20 L/min but remained low at the feet. With both ventilation rates, the lowest concentrations were detected under VAPOX.

under NRM and face-covered BiPAP, HFNC, and NCO; whereas the aerosols were distributed in a round shape under BiPAP and CPAP. The medical personnel could inhale substantial viral aerosols from a patient within 75 cm when applying BiPAP with face coverings at minute ventilation of 10 L/min, and within 1 meter when applying

BiPAP without face coverings at minute ventilation of 20 L/min (Table 1). Interestingly, with a higher minute ventilation of 20 L/min, the visible dispersion distances were shorter in the use of BiPAP with a face covering and CPAP oxygenation (Table 1). The analysis of the results from particle image velocimetry revealed that with minute ventilation of 20 L/min, the aerosol flow was stronger and more concentrated under CPAP and BiPAP oxygenation. The aerosols ejected to a maximum height of 36 cm under CPAP oxygenation (Figure 2) and then converged with the downward flow from the top of the room and moved rapidly to the feet side of the mannequin beyond visualization (Table 2). As for BiPAP, the aerosol flow ejected directly to the top via exhalation port and lingered at the head side of the mannequin; thus, the concentration accumulated; while BiPAP with face coverings, the aerosols dispersed from the lateral side of the face mask to the ground. Under HFNC oxygenation and NCO with face coverings, aerosols dispersed from the nostrils of the mannequin to the trunk and feet. In the use of NRM oxygenation, the aerosol flow moved to the head via holes on the upper part of the mask in the sagittal plane and was compatible with the concentration result (Figure 2).

Unlike dispersion distance, aerosol concentrations can be correlated with aerosol exposure and may be a better indicator of transmission risk. However, they have rarely been examined. As mentioned, we measured aerosol concentrations under 8 oxygenation settings at the head, trunk, and feet of the mannequin and used a reference group (ie, no oxygenation) for comparison (Table 2). In general, despite using the oxygenation devices or not, the highest concentrations were observed at the feet (the mannequin was face up at an incline of 30°). Notably, the exceptions were NRM, BiPAP, and BiPAP with a face covering, which concentrations were higher at the head of the mannequin than at the trunk or feet because the holes at the top of the mask allowed for air leakage (Table 2).

In general, BiPAP and face-covered BiPAP had the highest aerosol exposure at the head of the mannequin. The CPAP and face-covered HFNC oxygenation had the highest aerosol exposure, especially at the feet of the mannequin, compared with the use of the other devices and no oxygenation (Figure 3A and Table 2). Therefore, the health care personnel should be aware that aerosol exposure is highest at the feet of patients undergoing oxygenation therapy and should not overlook the importance of wearing personal protective equipment in the use of CPAP and HFNC oxygenation with face coverings. Relative to the reference group, aerosol concentrations were lower at the head and increased at the trunk and especially feet under NCO with face coverings

(Table 2). Aerosol concentrations under NRM oxygenation were generally low. As shown in the box plot (Figure 3A), VAPOX with a good mask seal showed no visible dispersion, and the aerosol concentration was lower than all the other oxygenation devices, including the reference group (Figure 2, Tables 1 and 2). Thus, VAPOX can be considered a proper choice for transient preoxygenation.

The HFNC oxygenation and NCO with face coverings were commonly used devices to treat hypoxia of patients with COVID-19. The HFNC oxygenation can obviate the need for intubation in patients with COVID-19 and was reported to be safe in one clinical study.[30,32,39] However, high-flow devices may endanger the health care personnel (as indicated by aerosol concentrations and dispersion distance) and should be used with caution. The loose connection of the nasal cannula to the patient's nostrils allows aerosols to spread in an elongated pattern to the trunk and especially the feet under face mask coverings (Tables 1 and 2).

Designed as simplified versions of conventional ventilator systems, the BiPAP and CPAP devices deliver positive end-expiratory pressure through a single-limb circuit and, similar to the HFNC therapy, may obviate the need for intubation in patients with COVID-19.[29] Concentrated aerosols are released in gas form through an exhalation port on the mask (Figure 2). However, aerosols from the CPAP exhalation port ejected to the feet rapidly, while aerosols from the BiPAP exhalation port lingered at the head of the mannequin. The VAPOX delivers positive end-respiratory pressure via a double-limb circuit (inhalation and exhalation), which can avoid aerosol ejection. The NRM and VAPOX oxygenations both provide a barrier protecting against aerosol exposure. However, these aerosols can still escape during NRM oxygenation, specifically from the 2 holes at the upper part of the mask (Figure 2). The VAPOX provides a tighter fit over the face, thereby better containing the aerosols.

The minute ventilation of patients with COVID-19, which tends to be higher than that of the general population, may decrease with worsening lung pathology and progression to respiratory distress or failure. As mentioned, we investigated the dispersion effect at ventilation rates of 10 and 20 L/min. As shown in Figure 2, the particle image velocimetry analysis indicated that aerosols were ejected in higher concentrations from the exhalation port of the CPAP mask under the higher ventilation rate. At a rate of 10 L/min, the aerosol concentrations remained lower than those in the reference group at the head and trunk (but not the feet) of the mannequin. At a rate of 20 L/min, the concentrations were higher than the reference concentrations at all positions

Table 3. The estimated accumulation time for each oxygenation device needs to achieve the number of particles to infect an individual (Nf) at the head, trunk, and foot of the mannequin. The individual was assumed to breathe at minute ventilation at 8 L/min (tidal volume 0.5 L × 16 inhalations/min). The emission rate of the patient with COVID-19 may range from 1,000 to 100,000 particles/min. The table was schemed at the emission rate of 1,000 particles/min. As the emission rate increased 10 times, the accumulation time would become 1/10. The Nf of SARS-CoV-1 and influenza were 100～1,000 particles. The Nf of SARS-CoV-2 was unknown; however, it was thought to be more efficient, thus causing the worldwide pandemic.

Minute Ventilation = 10L/min								Minute Ventilation = 20 L/min						
Nf=20	Nf=50	Nf=100	Nf=500	Nf=1000	Nf=5000				Nf=20	Nf=50	Nf=100	Nf=500	Nf=1000	Nf=5000
4.18	**10.45**	**20.90**	**104.48**	**208.96**	**1044.80**	**Reference***		**Reference***	**2.76**	**6.89**	**13.78**	**68.91**	**137.81**	**689.06**
7.63	19.08	38.16	190.80	381.60	1907.99	CPAP	**H**	CPAP	2.47	6.17	12.34	61.72	123.45	617.25
2.30	5.74	11.48	57.41	114.82	574.10	BiPAP		BiPAP	2.37	5.93	11.85	59.26	118.53	592.63
3.21	8.03	16.06	80.28	160.55	802.75	BiPAP†	**E**	BiPAP†	3.02	7.55	15.10	75.52	151.04	755.21
3.33	8.33	16.66	83.29	166.57	832.87	HFNC30†		HFNC30†	3.02	7.55	15.10	75.50	151.00	754.98
4.41	11.01	22.03	110.15	220.30	1101.50	HFNC70†	**A**	HFNC70†	2.28	5.70	11.40	57.00	114.00	570.00
7.72	19.31	38.62	193.10	386.20	1930.98	NC†‡		NC†‡	4.52	11.29	22.58	112.92	225.84	1129.22
5.63	14.09	28.17	140.87	281.73	1408.67	NRM§	**D**	NRM§	4.19	10.49	20.97	104.87	209.75	1048.73
23.72	59.30	118.61	593.04	1186.07	5930.35	VAPOX		VAPOX	8.79	21.98	43.96	219.80	439.60	2198.00
7.34	**18.36**	**36.71**	**183.56**	**367.12**	**1835.59**	**Reference***	**T**	**Reference***	**4.42**	**11.05**	**22.10**	**110.51**	**221.03**	**1105.14**
8.78	21.95	43.90	219.49	438.98	2194.91	CPAP		CPAP	3.48	8.69	17.38	86.92	173.84	869.21
7.84	19.60	39.20	195.99	391.98	1959.92	BiPAP	**R**	BiPAP	5.68	14.20	28.41	142.03	284.05	1420.26
12.83	32.06	64.13	320.63	641.26	3206.28	BiPAP†		BiPAP†	9.00	22.51	45.02	225.10	450.19	2250.95
4.08	10.20	20.41	102.03	204.05	1020.26	HFNC30†	**U**	HFNC30†	3.48	8.70	17.40	87.01	174.02	870.12
3.53	8.83	17.67	88.35	176.70	883.48	HFNC70†		HFNC70†	3.09	7.73	15.47	77.33	154.66	773.31
4.18	10.46	20.92	104.60	209.20	1046.01	NC†‡	**N**	NC†‡	7.40	18.51	37.02	185.08	370.15	1850.76
16.00	39.99	79.98	399.92	799.85	3999.23	NRM§		NRM§	10.35	25.88	51.76	258.82	517.64	2588.21
19.36	48.41	96.82	484.08	968.17	4840.83	VAPOX	**K**	VAPOX	12.91	32.28	64.56	322.78	645.56	3227.81
3.80	**9.50**	**19.01**	**95.05**	**190.09**	**950.47**	**Reference***		**Reference***	**1.84**	**4.60**	**9.20**	**45.98**	**91.96**	**459.78**
1.76	4.40	8.80	43.99	87.98	439.92	CPAP	**F**	CPAP	1.41	3.52	7.05	35.24	70.49	352.44
6.38	15.96	31.92	159.59	319.17	1595.85	BiPAP		BiPAP	4.83	12.08	24.17	120.83	241.66	1208.31
10.21	25.52	51.05	255.23	510.45	2552.27	BiPAP†	**O**	BiPAP†	6.49	16.24	32.47	162.36	324.73	1623.63
3.38	8.46	16.92	84.58	169.17	845.84	HFNC30†		HFNC30†	2.77	6.93	13.85	69.27	138.54	692.70
2.51	6.28	12.56	62.79	125.57	627.86	HFNC70†	**O**	HFNC70†	2.29	5.72	11.44	57.22	114.44	572.19
3.65	9.14	18.27	91.37	182.74	913.72	NC†‡		NC†‡	3.99	9.97	19.93	99.65	199.31	996.54
8.18	20.45	40.91	204.54	409.07	2045.36	NRM§	**T**	NRM§	5.23	13.07	26.15	130.73	261.46	1307.31
9.17	22.93	45.87	229.34	458.68	2293.41	VAPOX		VAPOX	6.97	17.42	34.84	174.22	348.43	1742.16

*Room air without oxygenation devices.
†Mannequin's face was covered with surgical mask.
‡NC at 15 L/min.
§NRM at 15 L/min

(Figure 2). This suggests that at different disease stages (with the corresponding deterioration in lung function), the risk of aerosol transmission from CPAP oxygenation can increase at higher ventilation volumes. Hui et al[33] (2019) examined the CPAP and HFNC oxygenation administered to a simulation mannequin with tidal volumes of 700, 300, and 150 mL to represent normal conditions, mild lung injury, and severe lung injury, respectively. Regardless of the setting, a lower tidal volume corresponded to a shorter dispersion distance.[37] This is in line with the results obtained under higher ventilation rates in the present study.

Figure 3B presents a comparison of aerosol concentrations under oxygenation therapy over time in a ventilated room (12 air changes per hour). Overall, aerosol concentrations were higher at a ventilation rate of 20 L/min than at a rate of 10 L/min, and concentrations tended to be higher at the head and feet of the mannequin than at the trunk. Notably, several surges in aerosol concentrations were observed at the head over a 3-minute interval under CPAP, BiPAP, BiPAP with face coverings, and HFNC oxygenation with face coverings. At the trunk with a mannequin ventilation rate of 10 L/min, the higher concentrations were observed under HFNC oxygenation and NCO with face coverings. When at a mannequin ventilation rate of 20 L/min, CPAP and face-covered HFNC oxygenation were higher than other devices. At the feet, CPAP and face-covered HFNC oxygenation were higher, and the NCO with face coverings was subsequently higher than other devices. Under NRM oxygenation, the concentration was higher at the head and lower at the trunk and feet. Several concentration surges were found at minute ventilation of 20 L/min at the head of the mannequin. The aerosol exposure was constantly low under VAPOX at all positions.

The number of virus particles needed to infect an adult individual (Nf) for SARS-CoV-2 remained unclear; thus, it was estimated to be $100 \sim 1,000$ copies following other coronaviruses, including SARS-CoV-1 and influenza virus.[36] At a viral load of 7×10^6 to 2.35×10^9 copies per milliliter, Stadnytskyi et al[40] estimated the virion aerosol droplets generated by loud speaking were at least 1,000 to 100,000 per minute. To translate our study result to clinically relevant interpretation according to Table 2, when medical personnel was at minute ventilation of 8 L/min (tidal volume 500 mL $\times$ 16 inhalations per minute) and the mannequin's minute ventilation of 10 L/min, the duration to achieve Nf=100 for VAPOX was 118.61 minutes at the head, 96.82 minutes at the trunk, and 45.87 minutes at the feet;

compared with the references group (no oxygenation) were 20.90 minutes at the head, 36.71 minutes at the trunk, and 19.01 minutes at the feet (Table 3). However, the duration to Nf may reduce dramatically if the aerosol droplet generating rate increased or the Nf was lower than expected. The NRM and VAPOX at the trunk and feet took more time to achieve Nf compared with CPAP, BiPAP, and BiPAP, HFNC, NCO with face coverings. The medical personnel should wear sufficient personal protective equipment and be aware of a higher risk of infection, especially applying oxygenation methods with strong flow, including CPAP, BiPAP, HFNC, and NCO, even with face coverings.

In conclusion, aerosol dispersion increased under oxygenation, especially at the mannequin's head and feet. Thus, health care personnel should remain vigilant and wear personal protective equipment at all locations around the patients. The CPAP, BiPAP, and HFNC therapy significantly increased aerosol exposure. Simply applying face coverings on the patient's face may not be a sufficient aerosol protection method. The aerosol exposure at the feet was lower under the NRM treatment. Moreover, the VAPOX was associated with significantly reduced aerosol exposure at the head, trunk, and feet, attributable to the container effect. In brief, CPAP, BiPAP, HFNC, NCO may accumulate minimum viral load more rapidly compared with NRM and VAPOX to infect medical personnel.

Author affiliations: From the Department of Emergency Medicine, Zhong-Xing branch, Taipei City Hospital, Taipei City, Taiwan; (Hung, W-L Chen, Wu, H-L Chen); the Faculty of Medicine, National Yang Ming Chiao Tung University, Taipei City, Taiwan (Hung); the School of Medicine, College of Medicine, Fu Jen Catholic University, New Taipei, Taiwan (Hung); the CrazyatLAB (Critical Airway Training Laboratory), Taipei City, Taiwan (Hung); the School of Medicine, Tzu Chi University, Hualien County, Taiwan (Su); the Department of Emergency, Dalin Tzu Chi Hospital, Buddhist Tzu Chi Medical Foundation, Chiayi County, Taiwan (Su); and the Department of Energy and Refrigerating Air-conditioning Engineering, National Taipei University of Technology, Taipei, Taiwan (Wang, Hu, Lin).

Author contributions: TYH, WLC, and HLC carried out the conceptualization of the investigation. SCH, TYH, WLC, YCS, TL participated in the design of the study. TYH, WLC, TYC, CCW, and HLC conceived the study and participated in its design and coordination. WLC, HLC, and TYH drafted the article. TYH and YCS participated in statistical analysis. TYH, HLC, and SCH carried out the overall supervision. All authors read and approved the final manuscript. TYH takes responsibility for the paper as a whole. HLC, SCH, TL are equally contributed and are considered as corresponding author.

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IMAGES IN EMERGENCY MEDICINE

DIAGNOSIS:

Hydropoint sign in hydropneumothorax. This ultrasonographic finding is used to identify the transition area between pneumothorax and pleural effusion pattern, indicating the presence of hydropneumothorax. The pathology is very rare, consists of the simultaneous presence of pneumothorax and pleural effusion, and is typically caused by trauma, thoracentesis, or bronchopleural or esophagopleural fistulae. Treatment is directed at underlying conditions, and large hydropneumothoraces often require drainage, whereas small versions may be observed.[1-3]

He was admitted to the hospital and discharged for home uneventfully after 7 days of supportive care.

Author affiliations: From the Emergency Medicine Department of Medicine (Rakphuak, Musikatavorn, Lumlertgul), Chulalongkorn University and King Chulalongkorn Memorial Hospital, the Thai Red Cross Society Thailand, Thailand.

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